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# TECHNICAL NOTE

## D-364

### FLIGHT MEASUREMENTS OF THE EFFECTS OF BLADE OUT OF TRACK ON THE VIBRATION LEVELS ON A TANDEM ROTOR HELICOPTER

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A flight investigation of the effects of blade out of track on the vibration level on a tandem rotor helicopter has been conducted. Blade out of track relative to a master blade was measured in flight as well as blade-fuselage clearances.

The flight results show that, for the test helicopter, values up to approximately 1 inch of blade out of track have a negligible effect on the vibration level. However, large amounts of out of track (2.0 inches) were found to increase the one-per-revolution (1-P) lateral vibration. Instantaneous out-of-track measurements show that the blades, relative to the master blade, appear to wander in a random fashion within small limits even though the blades, on the average, were in track.

Sample calculations are also presented and show a fair degree of correlation with 1-P flight vibration measurements in hover.

INTRODUCTION

In recent years, flight maintenance personnel have been tracking helicopter rotor blades, usually by using hand-held tracking flags, to values as small as  $\pm 1/8$  inch. In addition, some of the specifications for other types of tracking devices required accuracies as close as  $\pm 1/8$  inch. These close tolerances are required based on the assumption that a small amount of blade out of track would have a large effect on the helicopter vibration level. As the size of helicopters increases, the tracking of rotor blades by the hand-held-flag method becomes dangerous and inaccurate, particularly on a windy day. In addition, the measurement of the blade out-of-track values during flight requires the use of an electronic or optical type of blade tracker. Information on accuracies needed, or permissible variation between adjustments, thus, is of increasing importance.

In order to determine the effect of blade out of track on the helicopter vibration level, a flight investigation was undertaken to obtain vibration measurements during various flight conditions. During the flight investigation, the amount of blade out of track was measured by an electronic blade tracker. The tracker was also modified to measure the clearance between the blades and the fuselage during several abrupt maneuvers. In order to provide greater generality, comparisons of calculated and measured vibrations were made. The results of these investigations are reported herein.

### SYMBOLS

a	slope of lift curve, 5.73/radian
$a_0$	coning angle, deg
B	blade tip-loss factor
b	number of blades per rotor
$C_T$	thrust coefficient, $\frac{T}{\pi R^2 \rho (\Omega R)^2}$
c	blade section chord, ft
$d_F$	distance of front rotor path above reference, in.
$d_R$	distance of rear rotor path above reference, in.
$I_h$	mass moment of inertia of blade about flapping hinge, slug-ft <sup>2</sup>
L	lift per blade, lb
R	blade radius, ft
r	distance from center of rotation to measurement point, in.
s	distance traversed in t seconds, in.
T	thrust, lb
t	time for a blade to pass through the angle $\phi$ , sec

$V$	true airspeed of helicopter, ft/sec
$v$	induced inflow velocity at rotor, ft/sec
$x$	vertical distance, in.
$\ddot{x}$	vibratory acceleration, in/sec <sup>2</sup>
$\alpha$	rotor angle of attack; angle between axis of no feathering and plane perpendicular to flight path, positive when axis is pointing rearward, radians
$\gamma$	mass constant of rotor blade, $\frac{cpaR^4}{I_h}$
$\Delta H$	incremental lateral force, lb
$\Delta\theta_r$	incremental pitch angle at root, deg
$\theta_r$	pitch angle at root, deg
$\lambda$	inflow ratio, $\frac{V \sin \alpha - v}{\Omega R}$
$\mu$	tip-speed ratio, $\frac{V \cos \alpha}{\Omega R}$
$\rho$	mass density of air, slugs/cu ft
$\sigma$	rotor solidity, $bc/\pi R$
$\phi$	parallax angle, radians
$\Omega$	rotor rotational speed, radians/sec
1-P	one-per-revolution frequency, cps
3-P	three-per-revolution frequency, cps
Subscript:	
1	out-of-track blade

## EQUIPMENT AND INSTRUMENTATION

## Helicopter

A typical tandem helicopter with three-blade rotors was used for the investigation (fig. 1). The helicopter was equipped with production metal blades and was operated at a gross weight of 5,750 pounds for the tests. The blade mass and stiffness characteristics are shown in figure 2.

## Vibration and Blade Tracking Instrumentation

Motions of the structure were measured by using velocity-type pickups. Three components of velocity (vertical, longitudinal, and transverse) were measured at the front rotor, at the rear rotor, and at the pilot's seat (fig. 1). Time histories of the output of these velocity pickups were recorded by an oscillograph. Instrument frequency response corrections have been applied to all the data. This equipment is the same as that used in the investigation reported in reference 1.

In order to measure the relative track between the blades on each rotor, an electronic blade tracker (ref. 2) and associated equipment was installed in the helicopter. Photographs of the installation are shown in figure 3. Figure 3(a) shows the electro-optical pickup which senses the passage of each blade. The pickup was mounted at  $r = 132.5$  inches for the front rotor and at  $r = 136.5$  inches for the rear rotor. A phase detector mounted at the rear rotor measured the rotor rotational speed. The conversion unit combined the information from the pickup and the phase detector in a manner so as to solve the equation  $x = \frac{\Omega r t}{\phi}$ . (See fig. 3(b).) The conversion unit then compared  $x$  for any one blade with  $x$  for the master blade and this distance in inches was indicated on a meter on the face of the conversion unit. The master blade was the first blade to pass the electro-optical pickup after an electrical signal was transmitted from the phase detector. The absolute accuracy of the blade tracker was found to be about  $1/8$  inch at the measurement station (approximately  $1/4$  inch at tip) on the ground in flat pitch and normal operating rotational speed.

In order to measure blade-fuselage clearance an electro-optical pickup was modified. The sensing photoelectric cells were placed about 5 feet apart laterally on the outriggers shown in figure 3(a). The output of the photocells was recorded directly by an oscillograph and converted to blade height above a fixed reference.

## Vibration-Analysis Equipment

The vibration-frequency-analysis equipment consisted of a variable-filter-width heterodyne harmonic analyzer and associated playback and recording equipment. This device provides a reading of the mean square of the signal passed by a tunable filter with an accuracy of  $\pm 1/2$  decibel. The absolute accuracy with which the center frequency of the filter is known is estimated to be within 2 cps. In this case the data were analyzed at 10 times normal tape speed and therefore the center frequency is known to within 0.2 cps. This equipment is the same as that used in the investigation reported in reference 1.

## TESTS

### Flight Vibration Measurements

For the flight vibration portion of the tests the blades were initially set to track within  $\pm 1/8$  inch by the hand-held-flag method, and the vibration was recorded during hovering, transition, and at a forward speed of 45 knots. During the subsequent flights the second blade, after the master blade, on the front rotor to pass the optical pickup (hereinafter referred to as blade 2) was set out of track; the amount of out of track ranged from  $1/2$  inch to  $2\frac{1}{4}$  inches at the blade tip. The amount of out of track of blade 2 on the front rotor was checked by the hand-held-flag method. The flight plan for each flight was the same so that a comparison could be made of the measured in-track and out-of-track vibrations under similar conditions.

### Ground Vibration Measurements

Limited ground vibration tests to determine the lateral response of the structure for use in calculations were made with the same instrumentation that was used for the flight tests. The front rotor blades were removed and replaced by a fixed weight (100 pounds). The helicopter was supported on the tires for the tests, and an electronic shaker was used to provide a lateral excitation at the front rotor. The lateral response of the structure at the front rotor for the 1-P frequency was found to be about  $0.004$  g/lb.

## Blade-Fuselage Clearance

The clearance between the fuselage and rotor blades in abrupt maneuvers is of primary design interest. In order to ascertain the proximity of the blades to the fuselage and to get some idea of the feasibility of making measurements of this type, the modified optical pickup was installed on the test helicopter. With the pickup mounted on the outriggers, an accuracy of  $\pm 1/2$  inch in blade-fuselage-clearance measurement was obtained. For this part of the investigation the blades were set in track. The helicopter executed some abrupt maneuvers during which the clearance between the blades and a fixed reference on the fuselage was measured. The maneuver of most interest for this investigation was a landing approach and flare resulting in a hover. This maneuver, although not the most critical condition possible for blade-fuselage clearance, provides information on the clearance problem during abrupt transient conditions.

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## Relative Blade Track Measurements

In order to determine the relative blade track, the output signals from the electronic blade tracker were recorded on an oscillograph during the flight maneuvers performed in the vibration measurement tests. In addition, the relative blade track was measured in the vortex ring state. The displacement of the blades of the front rotor, relative to the master blade, was measured for the blades in-track condition and for each blade out-of-track condition.

## RESULTS AND DISCUSSION

The results of the investigation to determine the measured effects of blade out of track on vibration levels are presented for various flight conditions. Calculated effects of blade out of track on vibration levels are presented and compared with the measured effects. The results of the blade-fuselage clearance study and the results of the relative blade track measurements are also presented.

### The Effect on Vibration Level of Setting One Blade

#### on the Front Rotor Out of Track

Hover.- The effect of blade out of track on vibration level is shown in figure 4(a) for the hovering condition. It can be seen in the figure that as blade out of track increases the 1-P lateral vibration at the front rotor increases until the maximum vibration measured (about

0.17-inch double amplitude for 2.25-inch out of track) is reached. At the rear-rotor location there is some increase in the 1-P lateral vibration, varying from  $1/2$  to  $1/4$  of the increase at the front rotor. The maximum 1-P lateral vibration at the rear rotor (0.07 inch) was about 40 percent of the maximum 1-P lateral vibration measured at the front rotor (0.17 inch). This difference in the vibration present at the front and rear rotors for all out-of-track conditions is as expected, since the 1-P exciting force is at the front rotor and is not near the lateral fuselage resonant frequency. The 3-P lateral vibration at the front and rear rotors is not affected by blade out of track within the repeatability of the flight conditions.

The vibration in a vertical direction was measured at the front rotor only and these results are also shown in figure 4(a). There was no measurable 1-P vibration. The 3-P vibration at the front rotor in a vertical direction is of the same order of magnitude as the 3-P lateral vibration and does not appear to be affected by variations in blade out of track.

Transition.- In figure 4(b) the effect of blade out of track on vibration at a steady speed in the transition region is shown. The largest effect is at the front rotor where the 1-P lateral vibratory amplitude reaches 0.14 inch and to a lesser degree at the rear rotor where the lateral vibratory amplitude reaches 0.07 inch, both for a blade out-of-track value of 2.25 inches. There is no measurable 1-P vertical vibration at the front rotor. The 3-P component of vibration for the front and rear rotors laterally and for the front rotor in a vertical direction shows a small increasing trend with increasing blade out of track.

Forward speed of 45 knots.- The effect of blade out of track on vibration in forward flight at 45 knots is shown in figure 4(c). It can be seen that the 1-P component of vibration remains nearly constant at the front and rear rotors in a lateral direction until an out-of-track condition of about 1.5 inches is reached. When the amount of out of track is increased from 1.5 inches to about 2 inches the lateral vibration at the front rotor increases by a factor of about 2, whereas the lateral vibration at the rear rotor is only slightly changed. The amount of 1-P vibration present at the front rotor in a vertical direction for all out-of-track conditions is approximately one-half the lateral value. The 3-P component of vibration in figure 4(c) both laterally and vertically remains nearly constant over the range of out-of-track values.

Summary of effects on vibration levels.- In figure 4 it can be seen that the vibration level is not markedly increased up to an out-of-track value of 1 inch in hover and transition and 1.5 inches at a forward speed of 45 knots. This, in general, agrees with pilots' opinions of the

effects of blade out of track on vibration levels. Therefore, as far as vibration is concerned, there is little basis for using the effort necessary to keep blades tracked to very close tolerance at least for this size and type of rotor. It also seems that requiring accuracy of blade tracking devices of  $\pm 1/8$  inch may not be warranted.

### Calculated Effect on Vibration Due to Blade Out of Track

#### From Ground Response Measurements

The following numerical calculations are presented to show how the lateral response at the front rotor due to one blade out of track can be calculated for the hovering condition by using ground response measurements.

The sample calculations are based on the following conditions for the test tandem helicopter:

Weight, lb . . . . .	5,750
Number of blades per rotor . . . . .	3
Blade radius, R, ft . . . . .	17.5
Rotor solidity, $\sigma$ . . . . .	0.059
Tip-speed ratio, $\mu$ . . . . .	0
Rotor rotational speed, $\Omega$ , radians/sec . . . . .	28.6
Mass constant of rotor blade, $\gamma$ . . . . .	8.2
Thrust coefficient, $C_T$ (at sea level) . . . . .	0.00505

From reference 3, uniform inflow and zero blade twist being assumed, the thrust coefficient can be written as

$$C_T = \frac{\sigma a}{2} \left[ \frac{\lambda}{2} \left( B^2 + \frac{\mu^2}{2} \right) + \theta_r \left( \frac{B^3}{3} + \frac{\mu^2 B}{2} - \frac{4\mu^3}{9\pi} \right) \right] \quad (1)$$

Using  $B = 0.97$  and  $\lambda = -\sqrt{\frac{C_T}{2}}$  and solving equation (1) for  $\theta_r$  gives

$$\theta_r = 0.174 \text{ radian or } 10^\circ$$

A blade on the front rotor of the test helicopter was set out of track 2 inches by adjusting the pitch linkage. This adjustment in turn increased the blade pitch angle  $1^\circ$ . Therefore, the new pitch angle for this blade is  $\theta_{r,1}$  and the value is

$$\theta_{r,1} = \theta_r + \Delta\theta_r = 10^\circ + 1^\circ = 11^\circ$$

Also, from reference 3, a negligible effect of blade weight being assumed, the coning angle can be written as

$$a_o = \frac{1}{2} \gamma \left[ \frac{1}{3} \lambda B^3 + 0.08 \mu^3 \lambda + \frac{1}{4} \theta_r (B^4 + \mu^2 B^2 - \frac{1}{8} \mu^4) \right] \quad (2)$$

Substituting appropriate values into equation (2) gives

$$a_o = 5.5^\circ$$

When  $\theta_{r,1}$  is substituted for  $\theta_r$  in equation (1),  $C_T$  becomes  $C_{T,1}$  and is equal to 0.0057. When this value is used,  $a_{o,1}$  is found from equation (2) to be  $6.4^\circ$ .

The thrust per blade for the initial case is  $\frac{5750}{6}$  or

$$T \approx L = 958 \text{ lb/blade.}$$

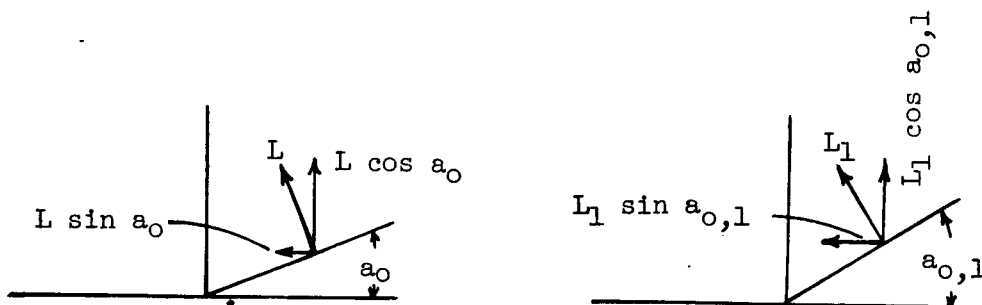
The calculated thrust per blade for  $C_{T,1} = 0.0057$  is  $\frac{6540}{6}$  or

$$T \approx L_1 = 1,090 \text{ lb/blade.}$$

The out-of-track blade on the front rotor results in an incremental lateral force  $\Delta H$  at the front rotor. This force  $\Delta H$  can be calculated in the following manner:

$$\Delta H = L_1 \sin a_{o,1} - L \sin a_o \quad (3)$$

The components of  $\Delta H$  are illustrated in the following sketches:



Substituting appropriate values into equation (3) gives

$$\Delta H = 1,090 \times 0.112 - 958 \times 0.096 = 30 \text{ pounds}$$

From ground response measurements the lateral response of the structure at the front rotor for the 1-P frequency is about 0.004 g/lb. The calculated vibratory response at the front rotor is  $\Delta H \times \text{Response (g/lb)}$ . Therefore  $\ddot{x}(\text{vibratory}) = 30 \times 0.004 = 0.12g$ . This value in terms of double amplitude displacement (x) at the 1-P frequency is 0.11 inch. This double amplitude displacement compares favorably with the 0.15 inch measured in hovering flight for 2 inches of out of track at the front rotor. (See fig. 4(a).)

#### Measurement of Blade-Fuselage Clearance

##### During an Abrupt Maneuver

Figure 5 shows a time history of blade height above the fuselage for each blade on the front and rear rotors and a time history of the airspeed as the helicopter makes a landing approach and flare maneuver. The data reveal that the front rotor blades do not come closer than 33 inches to the fuselage at any time during the maneuver. In the non-rotating condition, the clearance between the blade and the fuselage at the measurement station is approximately 20 inches. The rear rotor blades remain above 50 inches from the fuselage throughout the maneuver. These results show that there is no dangerous fuselage-clearance problems during this type of abrupt transient condition. Since the method provides a valid measurement of blade-fuselage clearance, it should be possible, through the use of proper circuitry, to present such clearance information to the pilot in other experimental or field applications if desired.

An additional item of interest, particularly from an aerodynamic-interference standpoint, is the spacing between the intermeshing rotor blade paths. Figure 5 shows that the paths are about 13 inches apart at the beginning of the test run. As the approach is started, the forward cyclic control causes the rearward part of the front path and the forward part of the rear path to move toward each other. Near the beginning of the flare, the paths of the rotor blades reach a minimum spacing of approximately 3 inches. The blade paths remain near this minimum spacing for about 2 seconds and then rapidly diverge and reach the maximum spacing (about 29 inches) about 4 seconds after the beginning of the flare.

### Measurement of Relative Blade Track

The measured blade track, relative to the master blade, during hovering, transition, and forward flight at 45 knots is shown in figure 6 as a function of time. The dashed line through the data shown in figure 6 is an average of all the instantaneous values of out of track for the blades other than the master blade which is represented by the solid line at a zero value of out of track.

Hover.- Figure 6(a) shows plots of instantaneous blade position relative to the master blade for several out-of-track settings of blade 2 on the front rotor in hover. When blade 2 was set approximately 1.5 inches out of track at the measurement station ( $2\frac{1}{4}$  inches at the tip by assuming a rigid blade), instantaneous out-of-track values ranged from 1.3 inches to 2.2 inches or an average of 1.75 inches at the measurement station. For an out-of-track setting of approximately 1.0 inch at the measurement station ( $1\frac{1}{2}$  inches at the tip), instantaneous out-of-track values ranged from 0.9 inch to 1.9 inches or an average of about 1.3 inches out of track for blade 2. In the case where the blades were set to track within  $\pm 1/8$  inch at the tips, the average instantaneous values at the measurement stations were 0.4 inch and 0.3 inch of out of track, respectively, for blades 2 and 3. In general, the average measured out-of-track values were less than 0.5 inch different from the values of out of track set by the hand-held-flag method at the measurement station.

Transition.- Figure 6(b) shows a similar plot of instantaneous blade position relative to the master blade for several out-of-track settings of blade 2 on the front rotor at transition speed. For a set out-of-track value of about 1.5 inches at the measurement station, instantaneous out-of-track values ranged from 0.6 inch to 1.75 inches or an average of about 1.2 inches out of track for blade 2. For a set value of about 1.0 inch of out of track, instantaneous values ranged from 0.35 inch to 1.3 inches of out of track or an average of about 0.7 inch for blade 2. When the blades were set to track within  $\pm 1/8$  inch on the ground, the average values of out of track were less than 0.4 inch for both blades 2 and 3. In general, the average measured out-of-track values were within 0.3 inch of the ground setting.

Forward speed of 45 knots.- In figure 6(c), plots of instantaneous relative blade out-of-track measurements for the front rotor in forward flight at 45 knots are shown. For a set value of 1.5 inches of out of track, instantaneous values of out of track ranged from -0.2 inch to 1.05 inches or an average of about 0.45 inch of out of track for blade 2. When blade 2 was set 1.0 inch out of track, instantaneous values ranged from -0.4 inch to 1.0 inch or an average of 0.3 inch. With the blades set to track within  $\pm 1/8$  inch, average values of out of track were less

than 0.2 inch for the blades other than the master blade. In general, the averages of the measured out-of-track values are far less than the set out-of-track values.

Effect of speed on measured out-of-track values.- A summary plot of the average out of track measured at the front rotor on blade 2 is presented in figure 7. In this figure, the average measured out of track for blade 2 is plotted against airspeed. From the figure, it is apparent that for a preset value of out of track, the measured out of track decreases as airspeed is increased.

Vortex ring state.- Figure 8 shows plots of blade position relative to the master blade for the front and rear rotors in the vortex ring state. The blades were set to track within  $\pm 1/8$  inch for this test. The figure shows instantaneous values of out of track ranging from about -1.4 inches to 2.0 inches for the front rotor and values ranging from about -1.3 inches to 1.5 inches for the rear rotor. The periodic manner with which these instantaneous values vary corresponds closely to the frequency of variation encountered in the other conditions. However, the amplitude of displacement is much larger in this condition. In general, however, the average values of out of track are within 0.4 inch of the zero value assigned to the master blade.

#### CONCLUDING REMARKS

Several flights have been made with a tandem helicopter in which one blade on the front rotor was deliberately set out of track for a range of values and the resulting vibration measured. In addition, some flight measurements of blade out of track relative to the master blade on the front rotor were made.

The results show that for values up to approximately 1 inch of blade out of track, the vibration level is not appreciably increased. It is therefore indicated that tracking rotor blades of this helicopter to values of less than  $1/2$  inch and to require much closer accuracy for blade tracking devices is unwarranted from the standpoint of reducing the vibration level.

Instantaneous values of relative out of track show that the blades appear to wander in a random fashion within small limits. The average of these instantaneous readings, however, does provide a good indication of relative track.

Measurements made indicate the feasibility of measuring blade-fuselage clearance. The results show that in an abrupt flare the blades come no closer than  $3/32$  inches to the fuselage of the test helicopter

as compared to a clearance of 20 inches between a blade and the fuselage in the nonrotating condition.

Sample calculations were made which show a fair degree of correlation between calculated and measured vibration level in hover due to blade out of track.

Langley Research Center,  
National Aeronautics and Space Administration,  
Langley Field, Va., January 22, 1960.

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Flight and Analytical Methods for Determining the Coupled Vibration Response of Tandem Helicopters. NACA Rep. 1326, 1957.  
(Supersedes NACA TN 3852 by Yeates and NACA TN 3849 by Brooks and Houbolt.)
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3. Wheatley, John B.: An Aerodynamic Analysis of the Autogiro Rotor With a Comparison Between Calculated and Experimental Results. NACA Rep. 487, 1934.

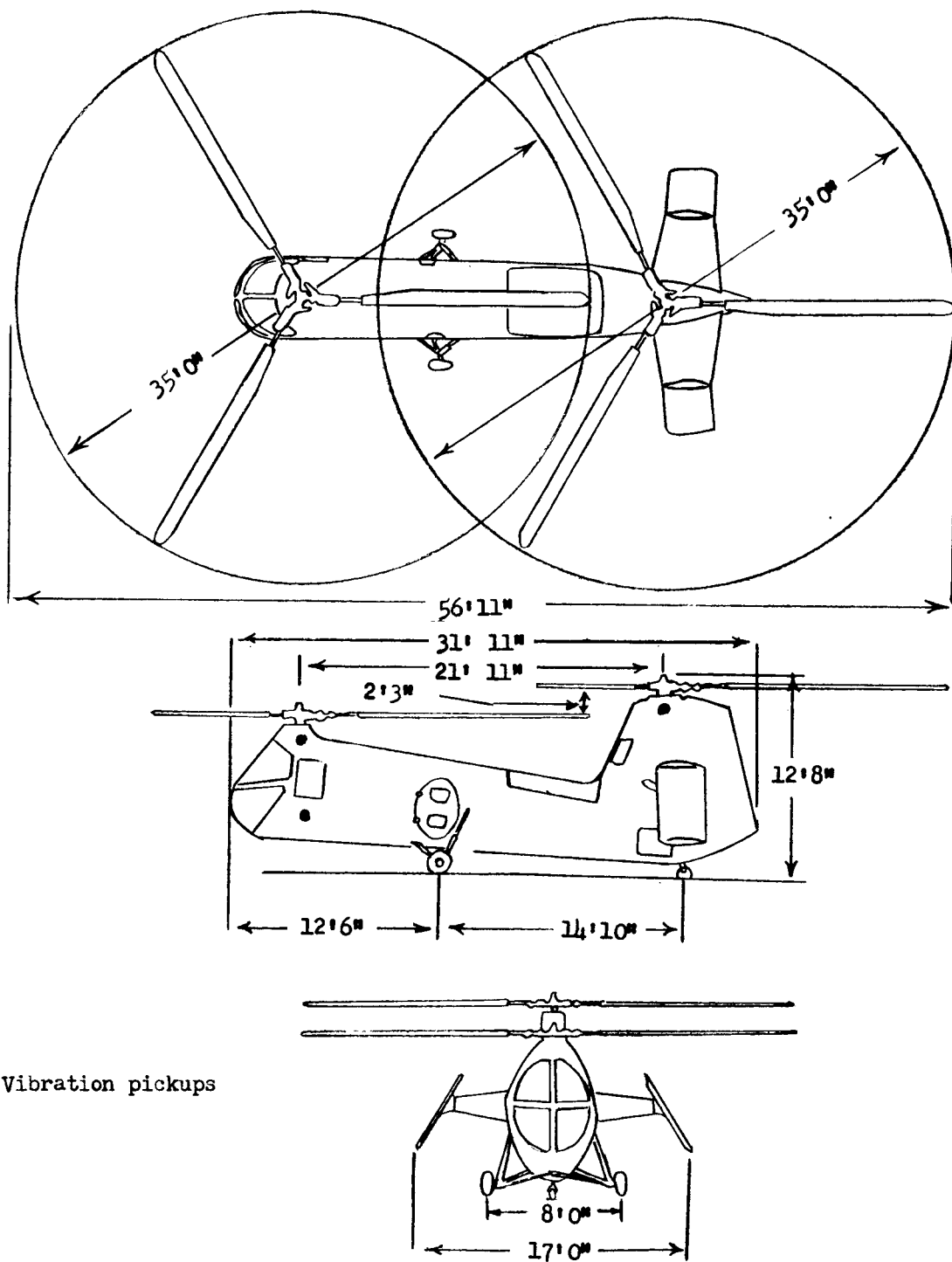


Figure 1.- Test helicopter showing location of vibration pickups.

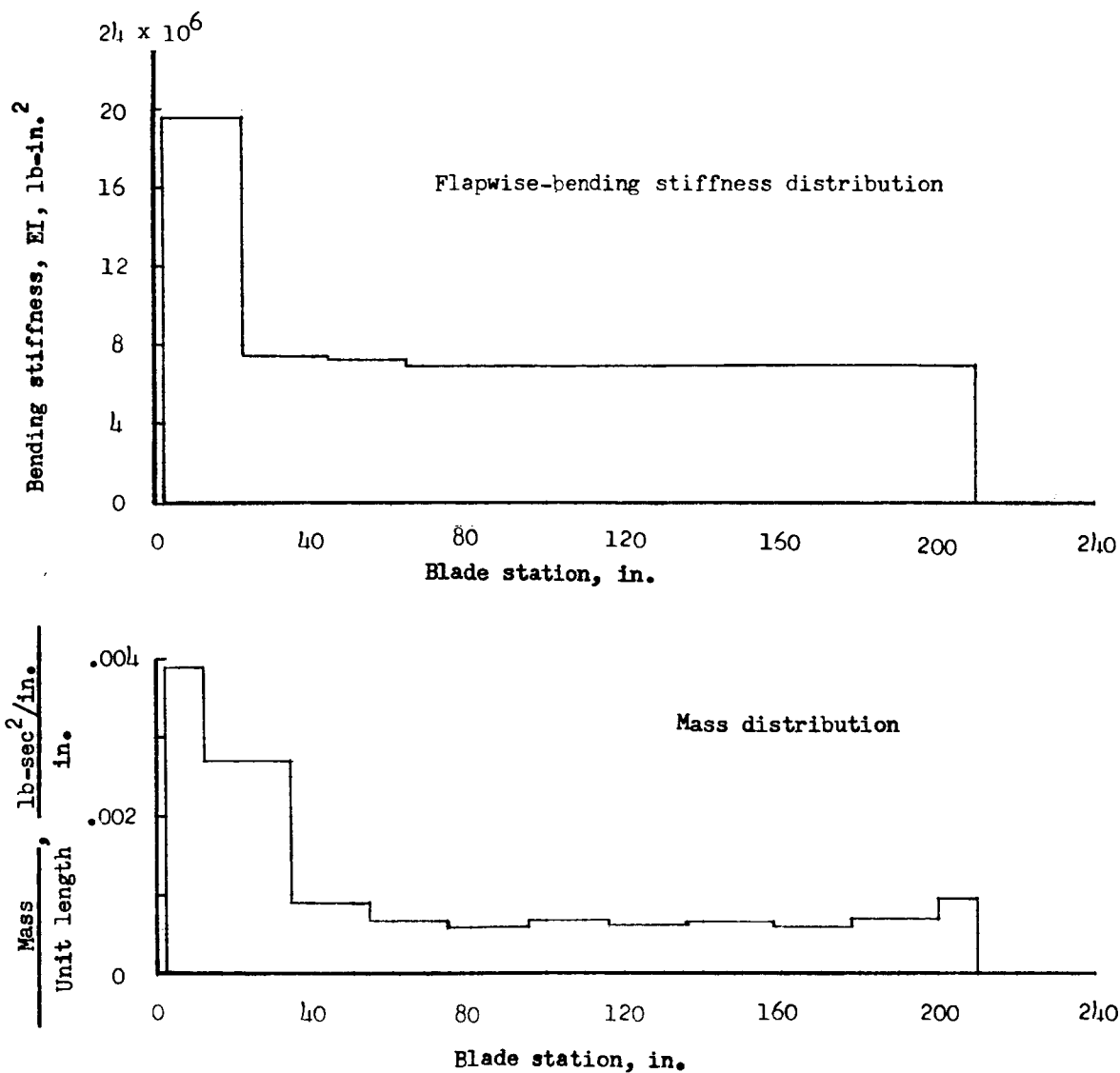
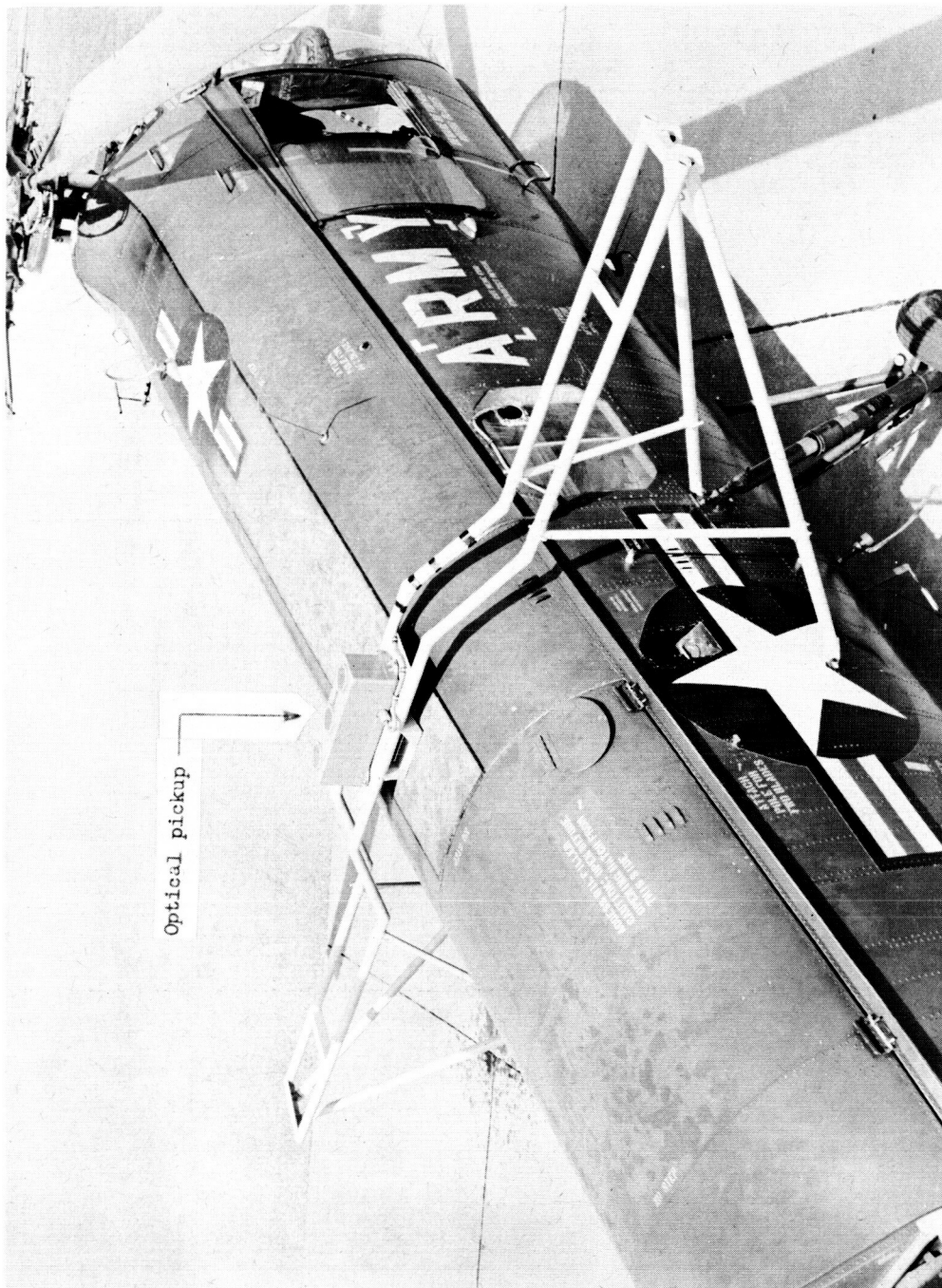


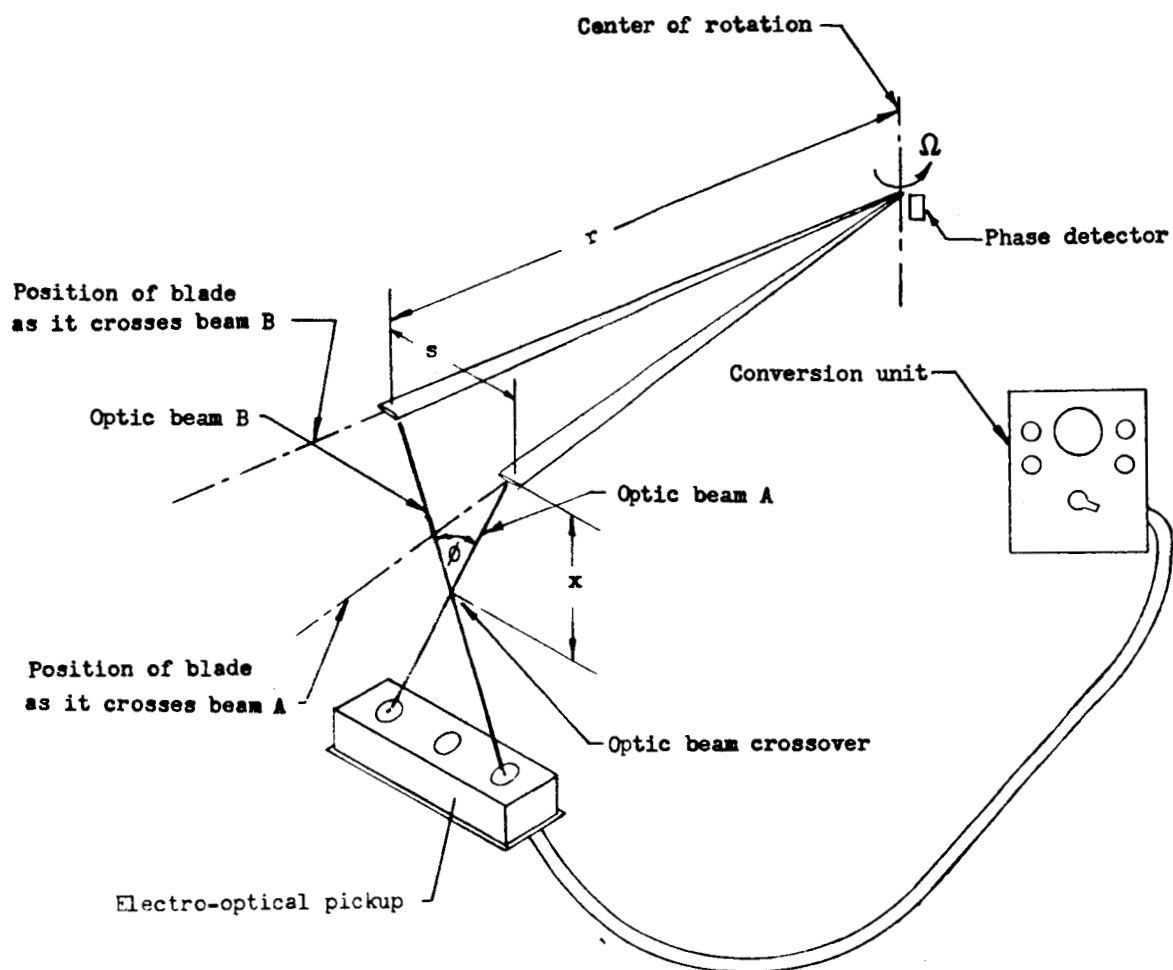
Figure 2.- Mass and stiffness characteristics of the blades used for the tests. Nonrotating fundamental natural frequency, 5.5 cps.



(a) Optical pickup.

L-57-2085.1

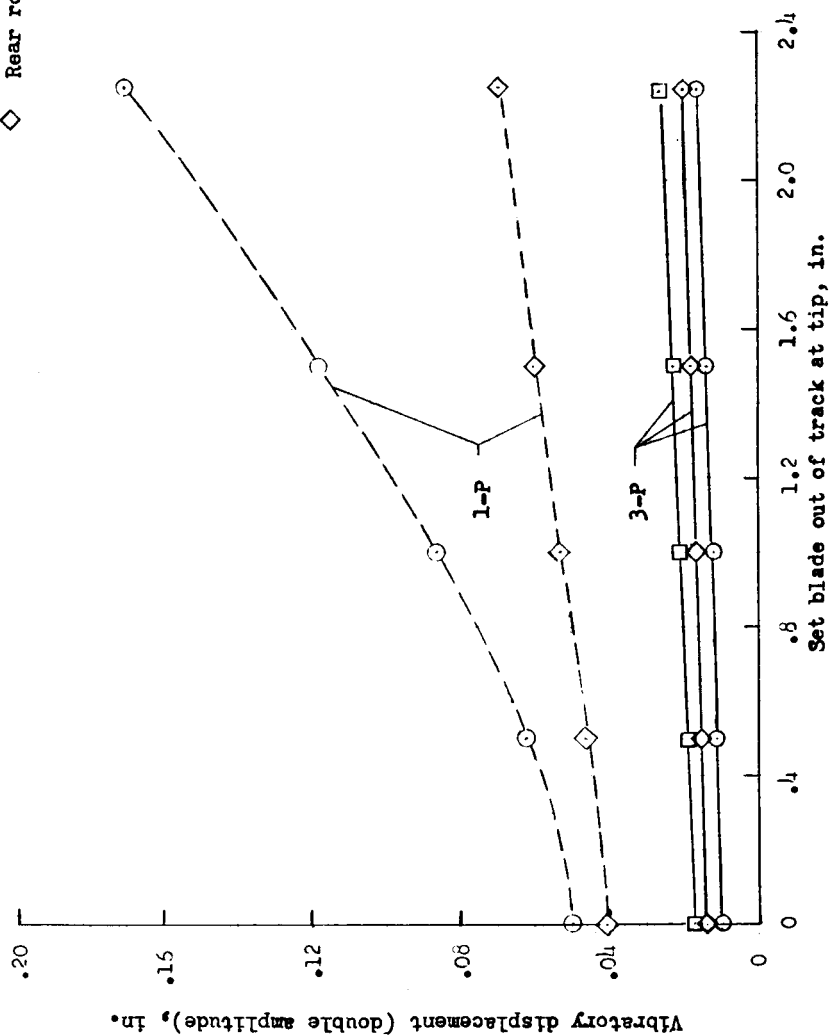
Figure 3.- Electronic-blade-tracker installation.



(b) Schematic diagram showing method of measurement of blade out of track.

Figure 3.- Concluded.

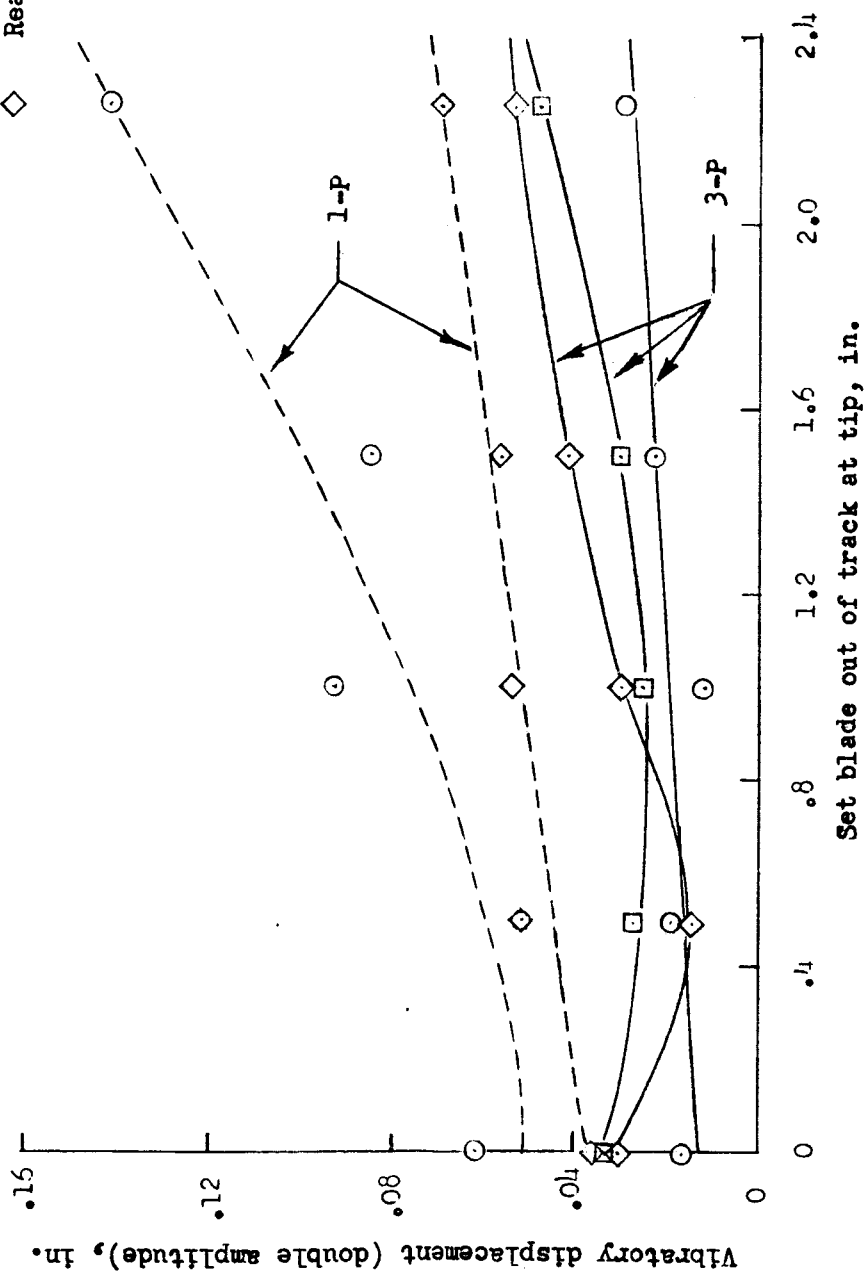
- Front rotor lateral
- Front rotor vertical
- ◇ Rear rotor lateral



(a) Hover.

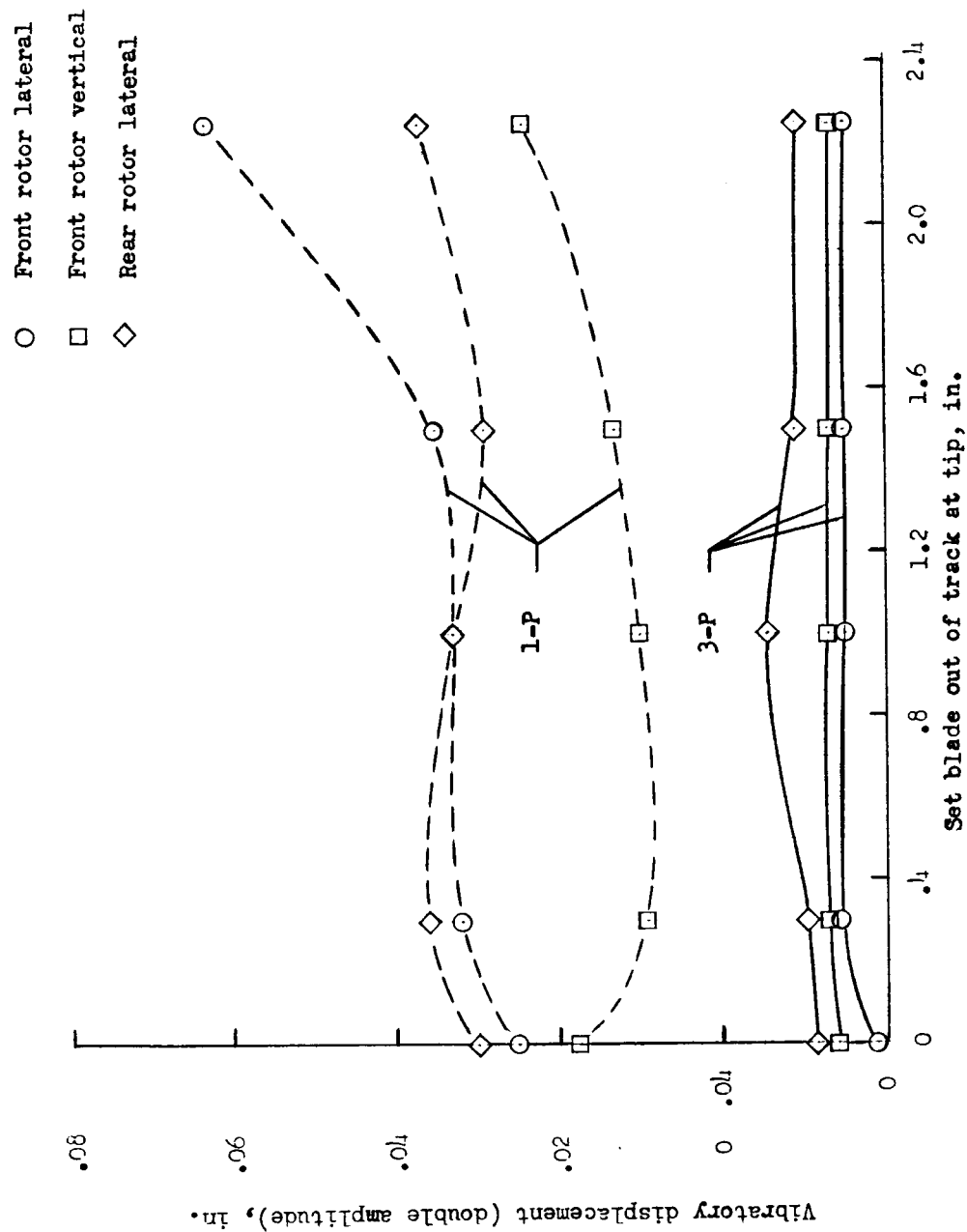
Figure 4.- The effect on vibration of placing one blade on the front rotor out of track for several flight conditions.

- Front rotor lateral
- Front rotor vertical
- ◇ Rear rotor lateral



(b) Transition speed.

Figure 4.- Continued.



(c) Forward speed, 45 knots.

Figure 4.- Concluded.

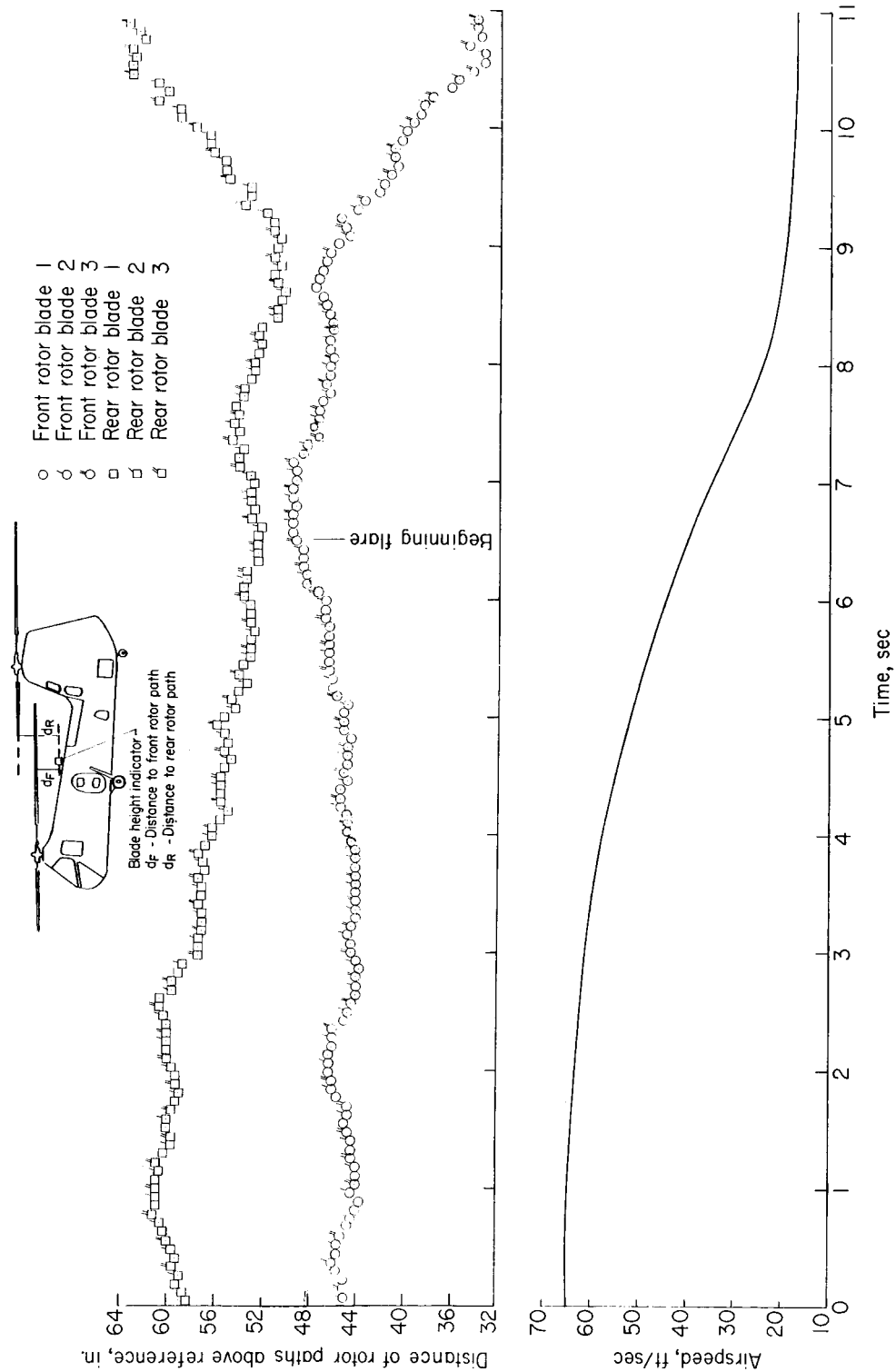
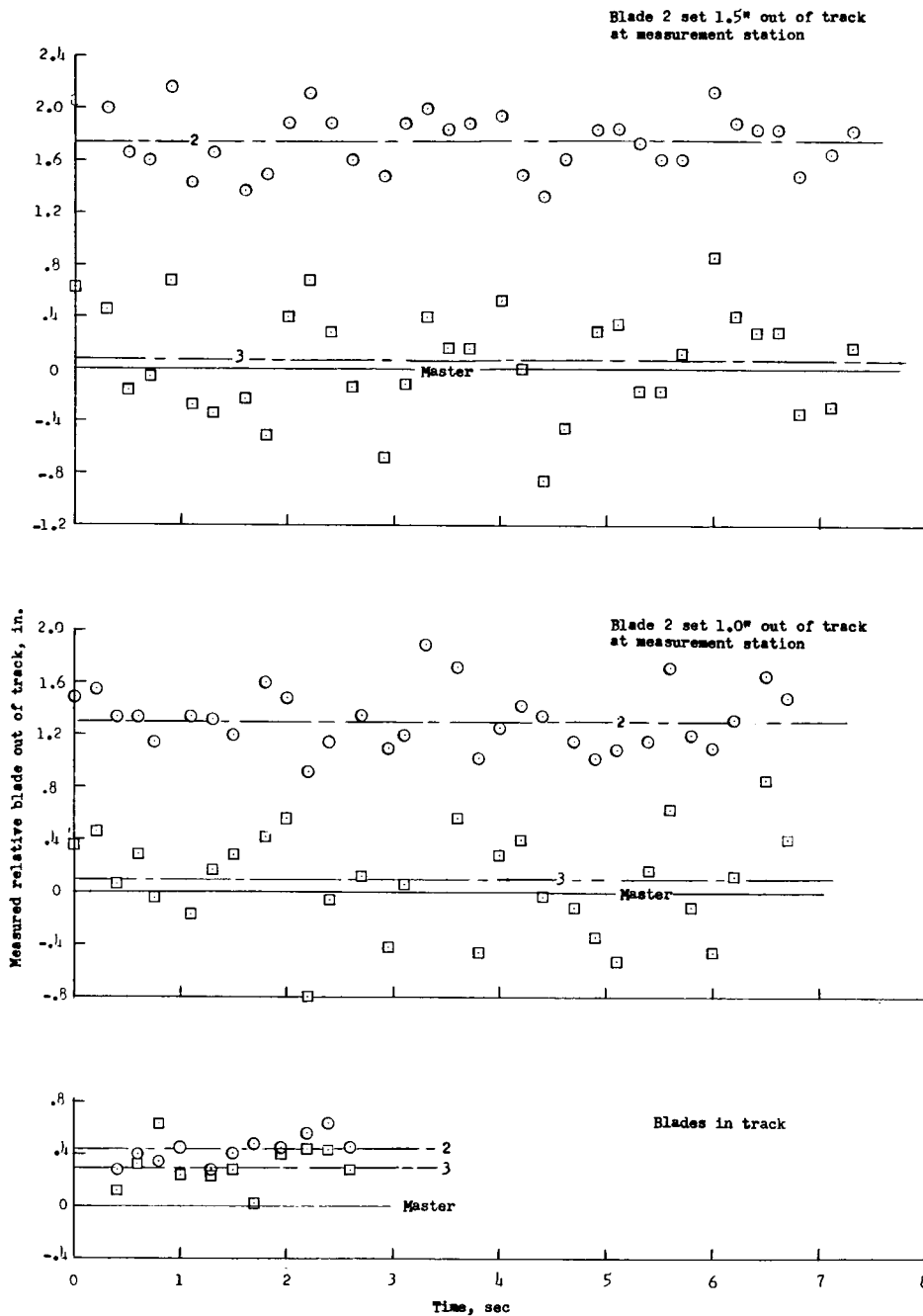
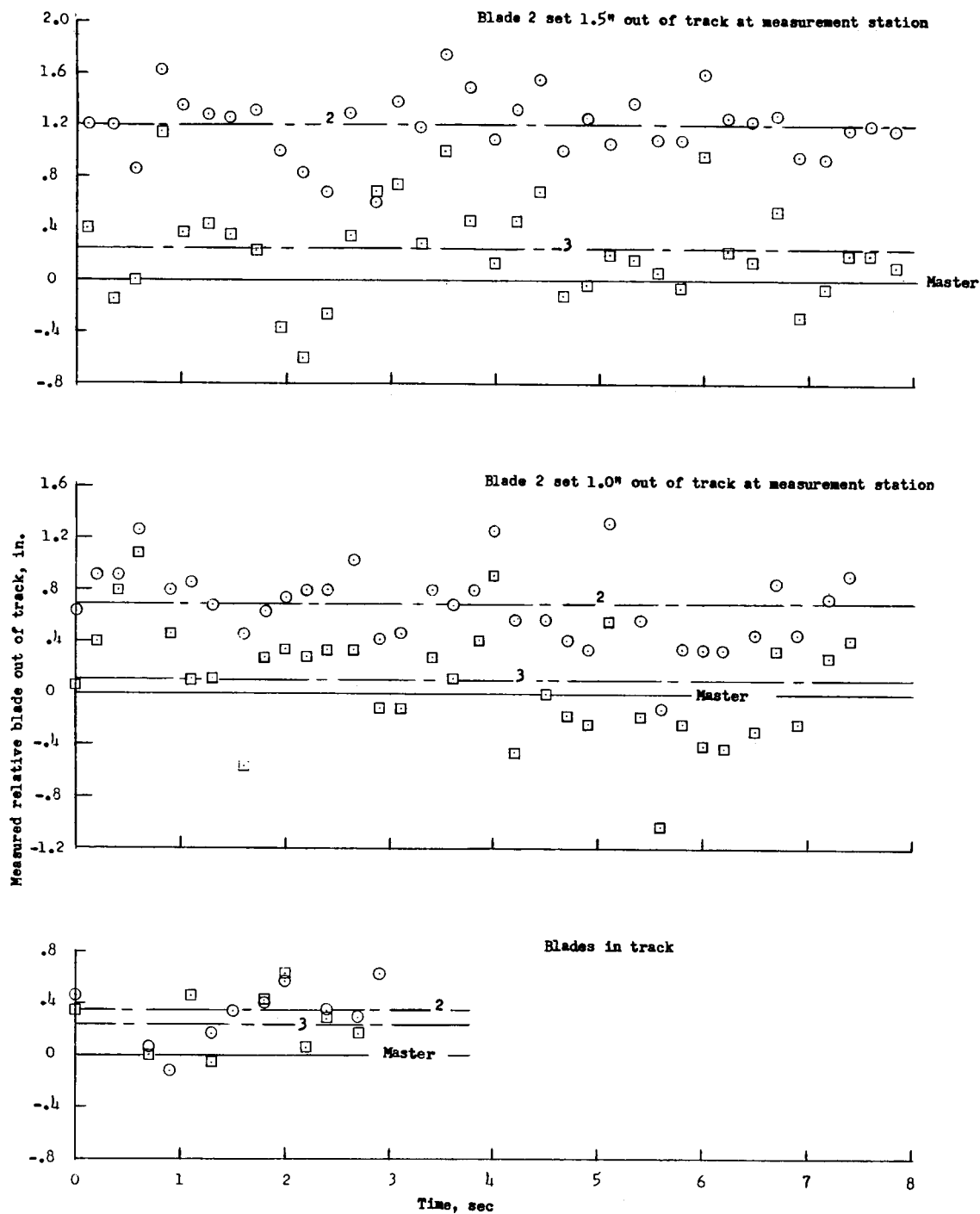


Figure 5.- Blade-fuselage clearance in a landing approach for the front and rear rotor.



(a) Hover.

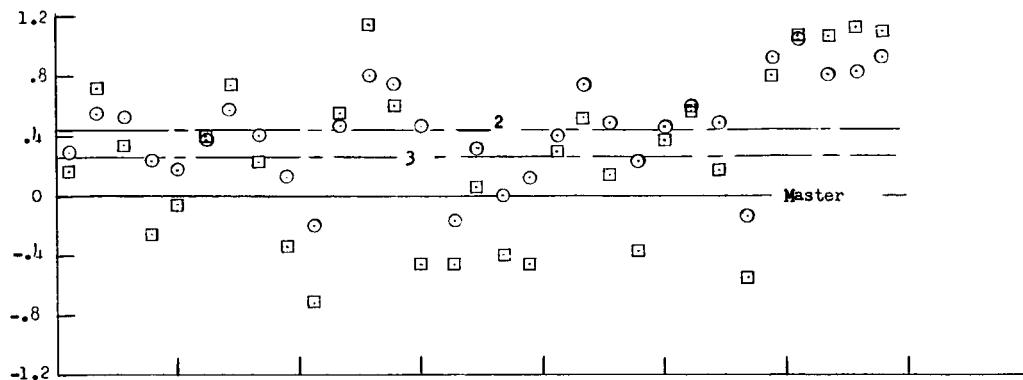
Figure 6.- Time history of the measured instantaneous out of track for the front rotor blades relative to the master blade for several flight conditions.



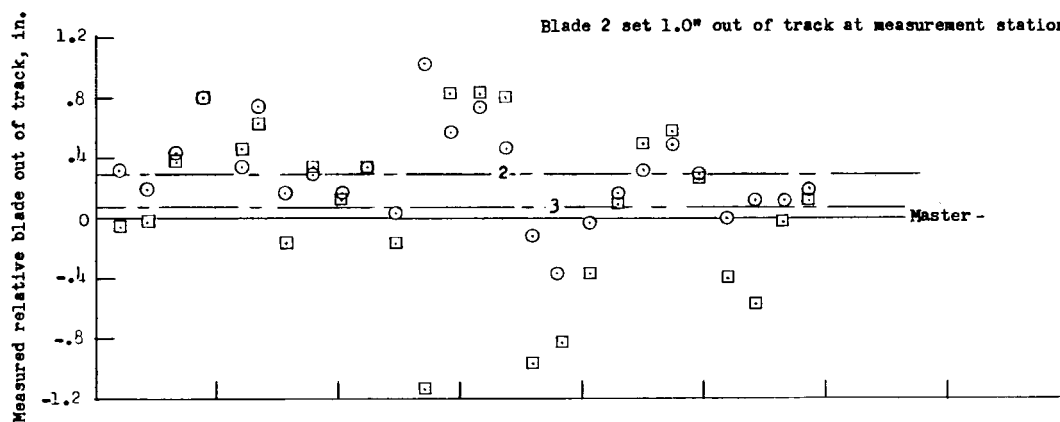
(b) Transition speed.

Figure 6.- Continued.

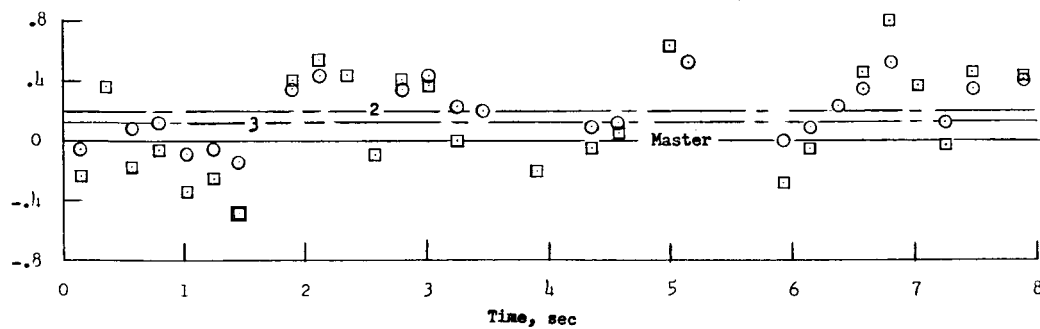
Blade 2 set 1.5" out of track at measurement station



Blade 2 set 1.0" out of track at measurement station



Blades in track



(c) Forward speed, 45 knots.

Figure 6.- Concluded.

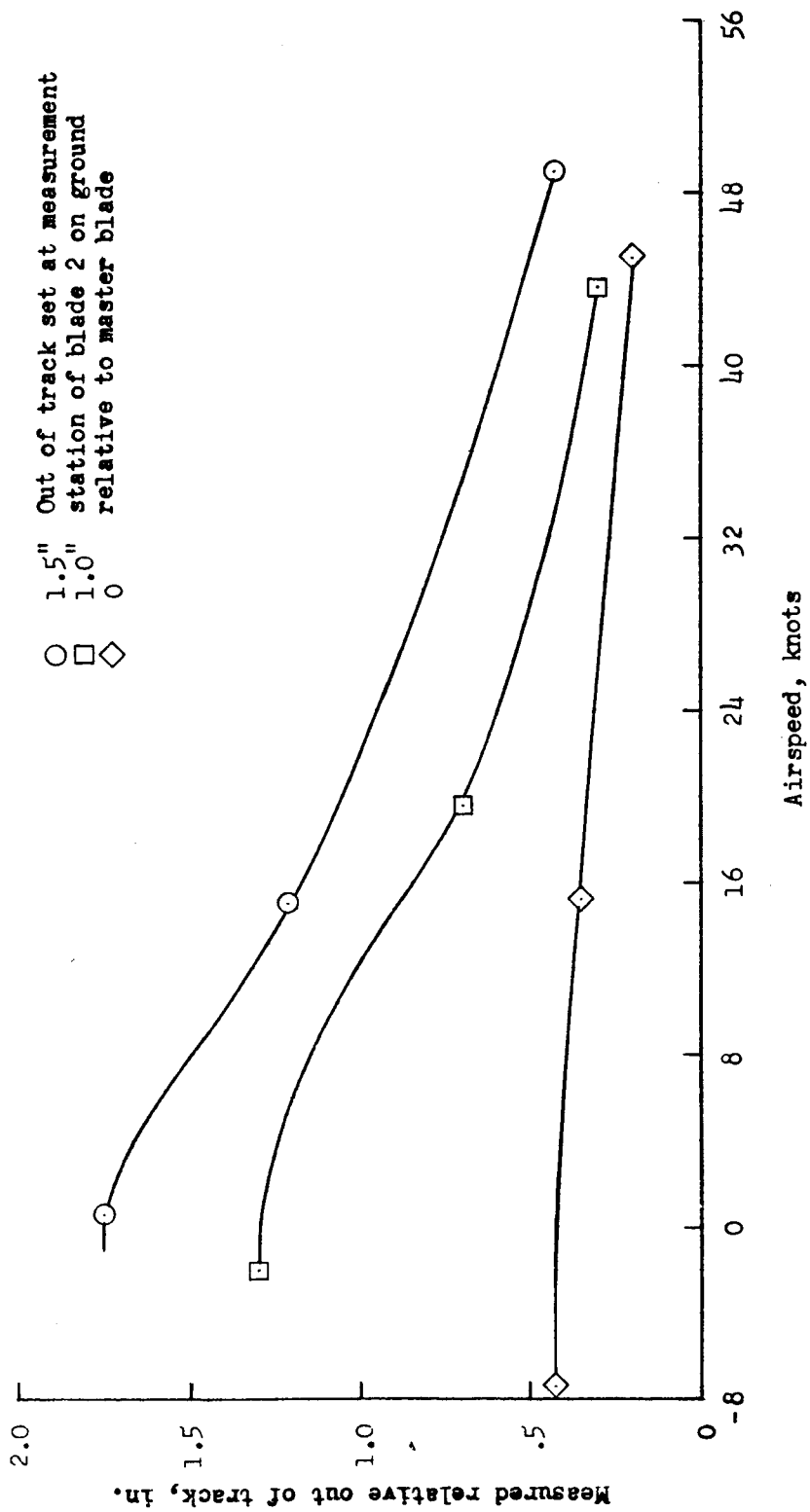


Figure 7.- Summary plot of relative blade track for several values of set out of track for a range of airspeeds.

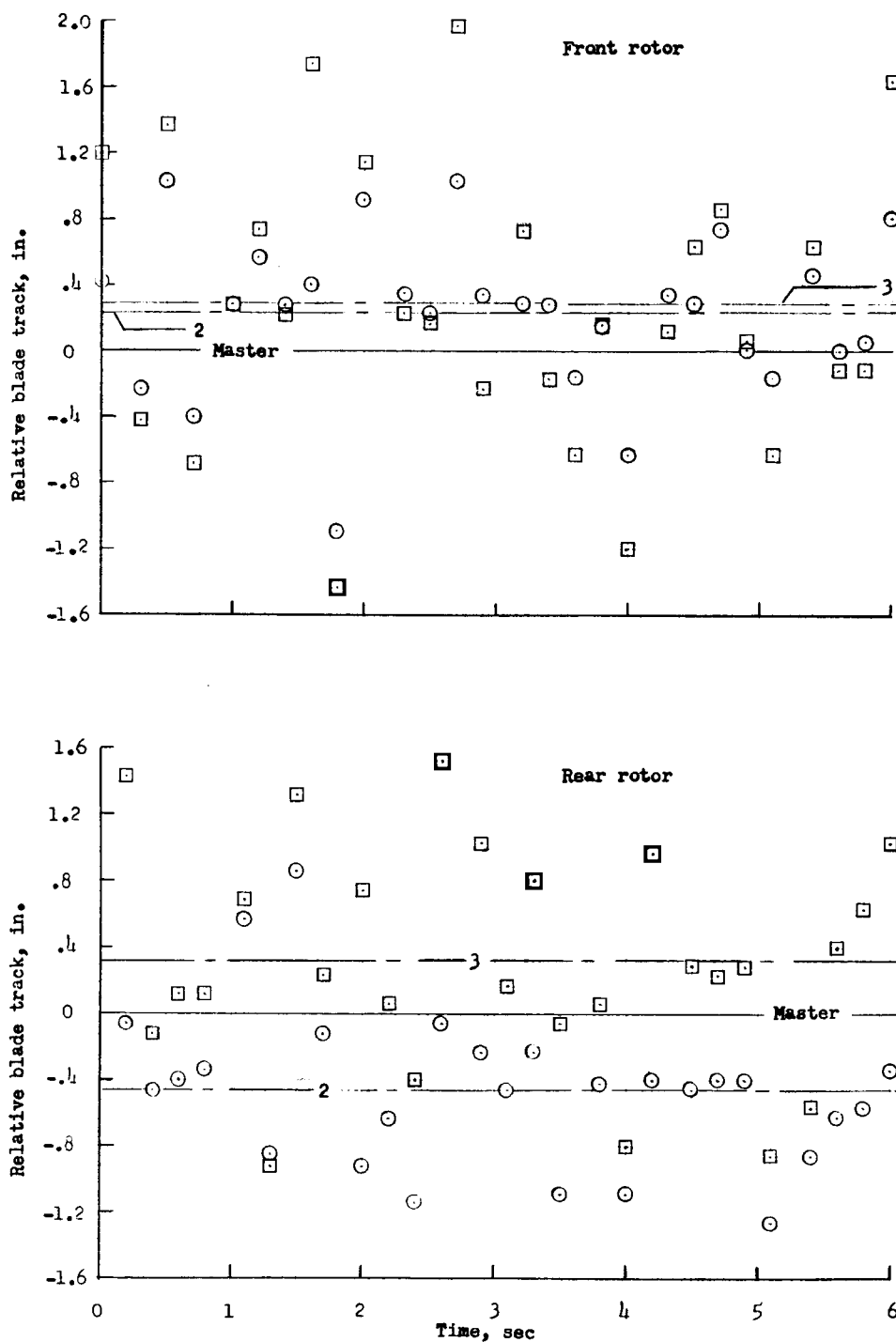


Figure 8.- Measured instantaneous blade track in the vortex ring state with all blades set in track on the ground.